Synthesis of TKE Dissipation Rate Observations in the Ocean's Wave Zone

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LONG-TERM GOALS

The goal of this project is to improve our understanding of turbulence and small scale processes in the aquatic near surface layer and their relation to surface waves and meteorological forcing. An improved understanding of these processes should result in the improvement of turbulence parameterization schemes used in the aquatic surface layer and, as a result, in more accurate model predictions.

OBJECTIVES

Our approach is to synthesize the available near-surface turbulence kinetic energy (TKE) dissipation data sets, along with their simultaneous meteorological, surface wave, and current measurements (when available). Then classify how various surface forcing conditions affect the results. Specific objectives of this analysis are to provide:

1) A consistent assessment of existing data sets.
2) Recipe/s of parameterization schemes of TKE dissipation rates, ε, as a function of the forcing (i.e. wind stress, wave age, wave height, buoyancy flux, stratification). Comparison to one-dimensional model runs, including surface wave effects, will help to reach this objective and may later be incorporated into three dimensional models.
3) Estimates of the fraction of the surface energy flux into the ocean (via the surface waves) which is parted to the mean and the turbulent flow.
4) Guidance for the design of future experiments to fill in currently existing gaps in our knowledge.

APPROACH

We have collected data sets from various investigators, who agreed to contribute relevant data, as well as from the published literature. Data includes near surface TKE dissipation rates measured from the following platforms: free rising/falling turbulence profilers, quasi-horizontal gliders equipped with shear probes and fast thermistors, submarine and ship-bow mounted turbulence sensors, acoustic travel-time current meters, and drag spheres. In some cases hydrographic data, comprising vertical profiles of temperature and salinity, and hence density, were available. Atmospheric boundary layer (ABL) fluxes (wind stress and heat flux) were available in some instances while for most only wind speed or surface stress data were available. For most data sets various measured wave parameters such as significant wave height, peak frequency (or period, or phase speed) were available while for the others only wave heights were available. Data were collected both in surface layers (SL) of the ocean and lakes, at various geographical locations, and under a variety of atmospheric and surface wave

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14. ABSTRACT
The goal of this project is to improve our understanding of turbulence and small scale processes in the aquatic near surface layer and their relation to surface waves and meteorological forcing. An improved understanding of these processes should result in the improvement of turbulence parameterization schemes used in the aquatic surface layer and, as a result, in more accurate model predictions.

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conditions. The latter is of importance since a variety of studies have shown a correlation between wave age and the rate of energy input from the wind to waves and hence to turbulence (e.g. Terray et al., 1997).
The available TKE dissipation rates, hydrographic, meteorological, wave, and data have been put into a database and Matlab programs were written to facilitate analyses and visualization of the data (see summary of available data in Table 1). The datasets facilitate statistical analysis of various parameters such as the distribution of TKE dissipation rates as a function of wind stress, wave height and age, stratification and stability in the oceanic boundary layer (OBL), etc.

Identification of the dominant forcing parameters (e.g. surface friction velocity, wave age, absence/presence of wind waves, absence/presence of swell) for each of the dissipation data sets allows the determination of the best apparent nondimensional parameterization groups on which to scale the dissipation in the wind-wave zone and the layer beneath it. Estimates of the dominant turbulence length scales and time scales involved in the near surface turbulence processes can be made and related to the observed dissipation rates and the pertinent forcing. For cases of enhanced TKE dissipation the datasets can be used to determine at what depth range, the commonly used constant stress layer scaling and/or convective scaling become valid.

Table 1. Summary of available meteorological and wave data for the various experiments analyzed (ranges are given in most cases): U_{10} is the 10- m wind speed, τ is the surface wind stress, u_{*w} is the water surface friction velocity, H_s is the significant wave height, T_p is the period at the peak of the wave spectrum, and F is the rate of wind energy input into the waves.

Instrument	U_{10} [m/s]	τ [N/m^2]	u_{*w} [m/s]	H_s [m]	T_p [m]	$F \times 10^4$ [m^3/s^3]	***Refer.***
Hot film anemometer	6.0	0.051	0.007	0.40	1.80	0.65	Stewart and Grant (1962)
Miniature dragsphere	5.8-11.2	0.069-0.237	0.008-0.015	0.26-58	1.7-3.3	0.65-3.23	Kitagorodskii et al. (1983)
Shear probes (free falling profiler)	8.6	0.104	0.010	3.3 (swell)	15.0 (swell)	6.94	Gregg (1987)
Shear probes (submarine)	5.2-8.2	0.041-0.102	0.006-0.010	0.56	4.0	0.77-2.97	Osborn (1992)
Shear probes (free rising profiler)	12.6	0.252	0.016	1.0 (wind) 3.0 (swell)	4.0 (wind) 12.0 (swell)	12.7	Anis and Moum (1995)
BASS and Dragsphere	6.9-15.7	0.104-0.902	0.010-0.030	0.16-0.49	1.4-2.4	0.96-18.2	Terray et al. (1996)
Acoustic current meter (bow mounted)	8.0-11.8	0.079-0.377	0.009-0.019	0.88-2.62	3.4-6.3	0.78-6.42	Drennan et al. (1996)
Shear probes (quasi-horizontal glider)	6.9-9.9	0.056-0.127	0.005-0.012	0.62-1.25	3.6-4.3	1.53-14.2	Greenan et al. (2001)
Shear probes (free falling profiler)	6.8-10.2	0.046-0.194	0.005-0.012	0.55-1.61	3.6-4.3	2.20-10.3	Greenan et al. (2001)
EM velocity probes (bow)	16.8-19.2	0.067-0.779	0.008-0.028	0.97-4.32	4.5-11.6	2.30-56.5	Soloviev and Lukas (2003)

Based on the wind and wave data, the fraction of the wind energy flux E_{10} in the ABL that is dissipated in the OBL under various wind/wave-age/wave-height conditions is quantified (These estimates range between, roughly, 1% to 10%; e.g. Anis and Moum, 1995). Currently researchers are in disagreement as to the amount of energy flux from the waves to the ocean (i.e. into the surface currents). For example Crawford and Large (1996) assume that only a negligible amount of the energy that enters the wave layer indeed goes into the ocean currents. Although this assumption may work well for climate models it disagrees with results from several experimental and theoretical studies and may be an inaccurate assumption for forecast models of currents and waves. More importantly, if indeed 10% of E_{10} is dissipated in the OBL this may well be a manifestation that a *non*-negligible amount of energy flux enters the ocean and goes either into the mean current field or into turbulence and in both cases TKE dissipation rates may be enhanced.

WORK COMPLETED

Most of the available data sets from various field experiments during which TKE dissipation rates and wave measurements were carried out in the near SL of ocean and lakes have been acquired (see Table 1 for a summary). A variety of instruments and platforms have been used to measure the TKE dissipation rates and while several of the data sets include detailed surface wave measurements, some had only wave estimates (height and period) from the ship's bridge observations. Wind speeds for the various data sets that were analyzed ranged from 5.2-19.2 *m/s,* and wave heights and periods were between 0.16-4.32 *m* and 1.4-15.0 *s*, respectively (see Table 1). Several of the TKE dissipation data sets include relatively shallow measurements on the order of a few significant wave heights (Drennan et al., 1996; Terray et al., 1996; Soloviev, 2003), while some of the data sets include deeper measurements (e.g. Anis and Moum, 1995; Greenan et al 2001; Gregg 1987) spanning the OBL. First, a comparison of the various data sets was carried out using a common framework of scaling TKE dissipation estimates in wall-layer coordinates in which the dimensionless TKE dissipation rate is given by $\varepsilon/(u_{*w}^3/\kappa z)$ and the dimensionless depth by gz/u_{*w}^2. If wall-layer scaling is indeed valid we expect that $\varepsilon/(u_*^3/\kappa z) \sim 1$. Fig. 1 shows this scaling for 6 of the datasets of Table 1.

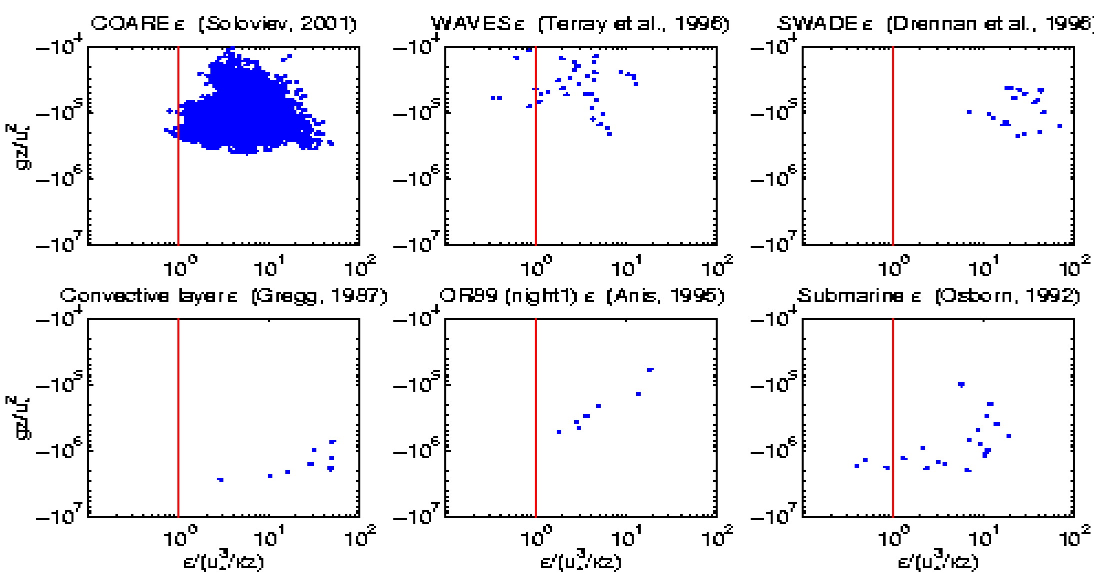

Figure 1. Dimensionless dissipation rate, $\varepsilon/(u_*^3/\kappa z)$, as a function of dimensionless depth, gz/u_*^2. The constant stress layer is represented by the vertical line (red), $\varepsilon/(u_*^3/\kappa z) = 1$ (ε is the TKE dissipation rate, u_* is the friction velocity in water, $\kappa = 0.4$ is von Karman's constant, and z is the depth). The upper panels represent dissipation estimates taken in relatively shallow depths (a few meters at most) from ship-bow mounted sensors and from moored instruments. The lower panels represent dissipation estimates made from profiling instruments, which on average extend to greater depths (10 m or more). Sources for the data sets are noted on the individual panels.

Next, we examined the statistical distribution of the scaled dissipations, which showed that the wall layer scaling severely underestimated TKE dissipation in the SL. More specifically, bootstrap statistics of the wall layer scaling show that mean values of $\varepsilon/(u_*^3/\kappa z)$ range from 3.6 and up to 34.5 (Table 2).

A different test of the validity of wall-layer scaling was carried out by examining the fraction of wind energy flux in the ABL, E_{10}, which is dissipated in the OBL ($E_{10} = \tau U_{10}$; τ is the surface wind stress and U_{10} is the wind speed at 10 m height). Wall layer scaling predicts the dissipation to be ~1% of E_{10} (Oakey and Elliott, 1982). Laboratory and field measurements in combination with a model used by Richman and Garrett (1977) predicted a higher percentage (4-9%). We have vertically integrated

Instrument	***E_{10} [W/m^2]***	***ε_I/E_{10} [%]***	***$u_*^3/\kappa z$*** x10^7	***$\varepsilon/(u_*^3/\kappa z)$***	***Reference***
Shear probes (free falling profiler)	0.89	14.6	0.90-34.2	30.2 (18.2-41.2)	Gregg (1987)
Shear probes (submarine)	0.21-0.83	5.97 (3.25-8.03)	0.63-49.4	3.6 (2.6-4.8)	Osborn (1992)
Shear probes (free rising profiler)	3.16	10.2	7.2-64.5	6.5 (3.1-10.8)	Anis and Moum (1995)
BASS and Dragsphere	0.72-14.2	1.94 (1.36-2.67)	12.0-1230	4.9 (3.4-6.7)	Terray et al. (1996)
Acoustic current meter (bow)	0.66-3.89	11.2 (7.92-15.1)	9.79-104	34.5 (23.3-50.0)	Drennan et al. (1996)
Shear probes (free falling profiler)	0.18-1.29	6.0 (3.9-8.4)	0.36-10.1	9.7 (6.7-12.9)	Greenan et al. (2001)
Shear probes (quasi-horizontal glider)	0.15-1.43	4.7 (2.5-7.5)	0.34-22.1	11.0 (9.1-13.4)	Greenan et al. (2001)
EM velocity probes (bow)	0.45-14.9	1.87 (1.84-1.89)	4.96-657	6.2 (6.1-6.3)	Soloviev and Lukas (2003)

Table 2. Summary of scaling results for various experiments. Variables are defined in the text (bootstrap mean values and 95% confidence intervals are given in parentheses).

dissipation rates, ε_I, in the SL (depths on the order of a few wave heights and less than 10 m for all sets in this analysis). The results are summarized in Table 2 and show that in the presence of waves the values are significantly higher than the wall layer predicted 1% (one has to consider ε_I computed here as a *lower* limit on the *total* wind energy flux dissipated in the OBL since we included only the SL).

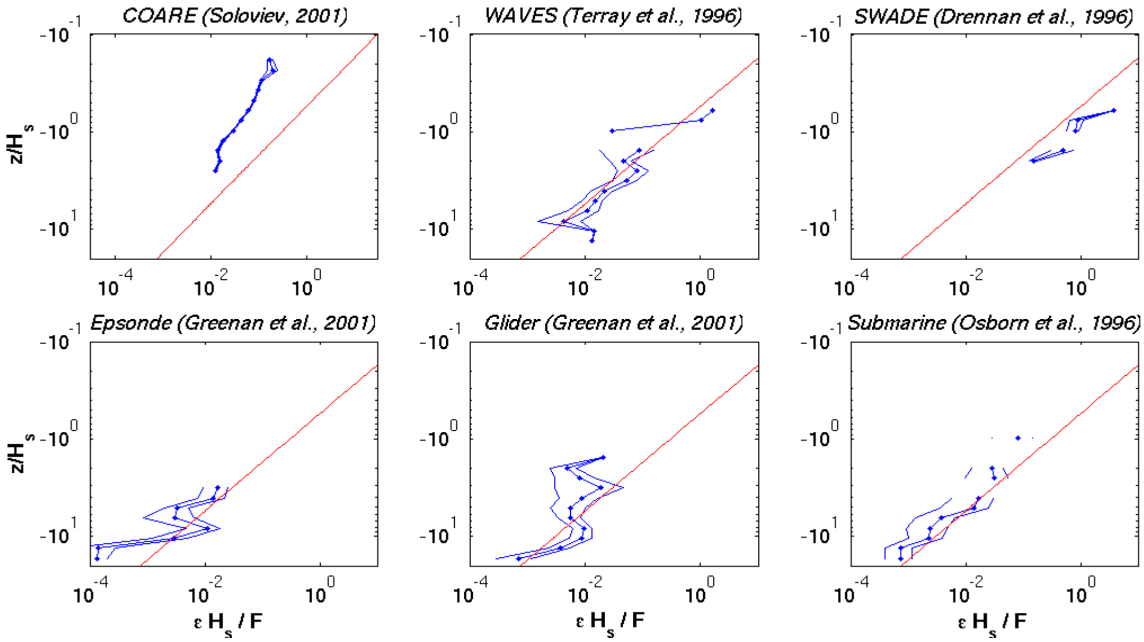

Figure 2. Example of dissipation rates vs. depth in the scaled wave coordinates of Terray et al. (1996). The solid line (red) represents the best fit of their WAVES data: $\varepsilon H_s/F = 0.3(z/H_s)^{-2}$.

Terray et al. (1996) suggested that in the presence of waves, when wall-layer scaling underestimates dissipation in the upper SL, TKE dissipation will be dependent on, *F*, the rate of energy input from the wind to the waves and, H_s. The following was found to hold: $\varepsilon H_s/F = 0.3(z/H_s)^{-2}$ for $z > 0.6H_s$ and $\varepsilon H_s/F = 0.83$ for $z \leq 0.6H_s$. Below the wave affected layer the "conventional" wall-layer may be valid. We have binned the scaled dissipation values, $\varepsilon H_s/F$ in scaled depth bins, z/H_s, and computed the mean and 95% bootstrap confidence intervals for each bin, using the values of *F* and H_s given in Table 1. Results of this scaling are presented in Fig. 2.

Profiles of TKE dissipation rates, ε, were modeled using the 1- dimensional turbulence model GOTM. The scheme used was the so-called generic two-equation model (for details see Umlauf and Burchard, 2003). Physically, the flow beneath the surface in presence of waves is taken as a generalization of pure shear-free turbulence. In our model runs we have "injected" TKE from the waves at several depths levels, z_0, expressed in terms of the significant wave height, e.g. $z_0 = 0.25H_s$ to $z_0 = 1.0H_s$. The injection level might be regarded as the so-called "breaking depth" (Terray et al., 1996). The magnitude of the TKE flux injected was taken simply as a constant factor, α, times u_{*w}^3, and spatial (vertical) TKE decay rates chosen were between -1 and -2 (See Fig. 3 and caption for details).

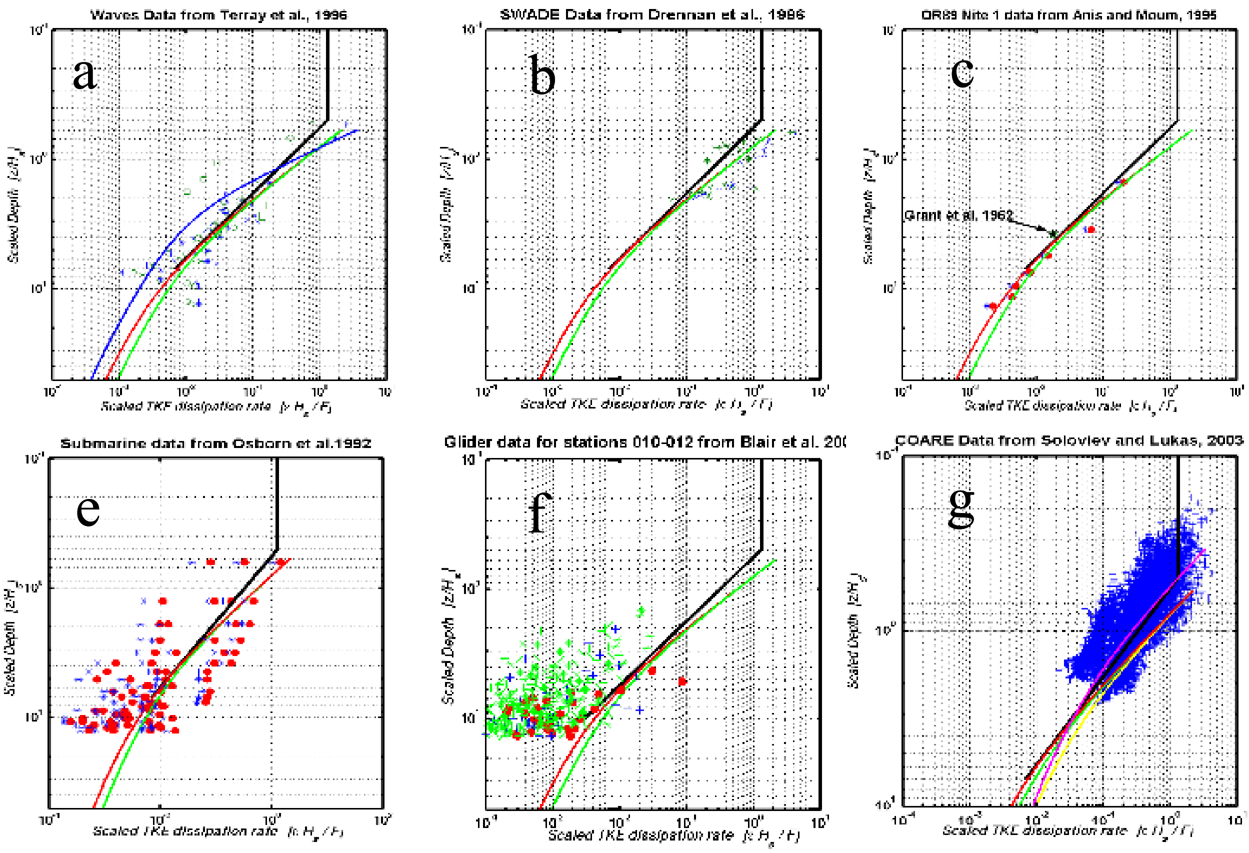

Figure 3. One dimensional turbulence model run results overlain with respective data sets (for all panels thex-axis is the scaled TKE dissipation rate, $\varepsilon H_s/F$, and the y-axis is the scaled depth, z/H_s). In all cases the green and red curves are for runs with injection of TKE flux, αu_{*w}^3, with α equal to 150 and 100 respectively. All TKE injections are at a depth of Hs/2 except for the purple curve on panel g where we used Hs/4. Observational data were scaled with F, when available, or by αu_{*w}^3, with α equal to 150 and 100, except for the COARE data (panel g) where we used $\alpha = 50$; the black heavy line represents the wave scaling as suggested by Terray et al., 1996. Note: model runs include both the shear-free wave effects and the shear generated TKE via the "regular" wall-layer mechanism.

RESULTS

Firstly, our results indicate that for the majority of the data sets analyzed here the widely used wall layer parameterization severely underestimates TKE dissipation rates in the layer beneath wind-waves. In most cases we found $\varepsilon/(u_*^3/\kappa z) >> 1$ down to depths of several wave heights, but usually confined to less than 10 m (exceptions are the observations of Gregg, 1987, when $\varepsilon/(u_*^3/\kappa z) >> 1$ down to depths of 25 m). Average dissipation estimates regularly exceeded $u_*^3/\kappa z$ by at least a factor of 4 while most where larger by an order of magnitude or so (largest value was more 30 times $u_*^3/\kappa z$).

The wave parameterization proposed by Terray et al. (1996) was found to hold for several of the data sets in which enhanced dissipation rates were observed (Fig. 3). Specific examples are the data sets collected from a submarine (Osborn et al., 1992), a free rising profiler (Anis and Moum, 1995), a quasi-horizontal glider (Greenan et al., 2001), as well as part of the data collected with the free falling Epsonde profiler (Greenan et al., 2001). An exception is data collected with the glider and Epsonde when swell was observed in addition to wind-waves. Another exception are the data from COARE (Fig.2, upper left panel; Soloviev and Lukas, 2003); Although no information regarding swell was available for COARE data, these data seem to mimic the behavior of data from Greenan et al. (2001) when swell was present, and lie consistently above the best fit of the WAVES data: $\varepsilon H_s/F = 0.3(z/H_s)^{-2}$**.** Another reason for this apparent discrepancy might be that a result of underestimating F, the rate of energy input from the wind to the waves. Here we have estimated F from the surface friction velocity and the significant wave height, which were the only available parameters. But, when we used $F = 50\, \boldsymbol{u_{*w}}^3$ to scale the observed COARE dissipation rates, the data seems to collapse around the scaling proposed by Terray et al. (1996) (Fig. 3g).

The one dimensional model runs using the GOTM turbulence model with the generic two-equation model seem to provide reasonable estimates of both the vertical rate of decay of dissipation as well as the right orders of magnitude. A transition to wall-layer behavior occurs at a depth of ~$10H_s$. We note that the runs that closely resemble the observed data exhibit a vertical decay rate of ~$z^{-2.5}$ and a TKE decay rate of ~z^{-1} (not shown). Injection depths of TKE flux of $z/H_s = 0.5$ were found to work well in most cases, except for the COARE data where $z/H_s = 0.25$ was found to produce better results. The sensitivity of various models and scaling to this parameter (in some cases referred to as the roughness length, z_0) has already been discussed in the literature.

Estimates of the fraction of E_{10} dissipated in the OBL suggested by Oakey and Elliott (1982), i.e. ~1%, was found to be an underestimate when SL dissipation values were taken into consideration. Most of the data sets examined show that 5% and up to more than 10% of E_{10} are in fact dissipated in the OBL. This conforms closely to the values suggested by Richman and Garrett (1977). Some of the data we have analyzed suggest that when the waves are fetch limited and/or relatively young, there might be a better conformity to features predicted for the wall layer (e.g the fraction of E_{10} dissipated in the OBL is closer to the predicted 1%). This behavior is consistent with other evidence (e.g. Thorpe, 1992) and we are currently examining the effect of wave age more closely.

IMPACT/APPLICATION

Results of this work will improve TKE dissipation parameterization schemes used in oceanic models and our understanding of turbulence and small-scale processes in the oceanic near surface layer in the presence of waves.

TRANSITIONS

Results are currently discussed with several other investigators in our research group.
A poster on "Statistics of Overturns, APEF, and TKE Dissipation in Stratified Flows" has been given at the AGU fall meeting, Dec. 2002.
A presentation on "**TKE Dissipation Rates in the Aquatic Wave Zone"** will be given at the Ocean Sciences Meeting in Jan. 2003.

RELATED PROJECTS

Other CBLAST projects.

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